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No. 852

EFFECTS OF RANGE OF STRESS AND OF SPECIAL NOTCHES ON FATIGUE PROPERTIES OF ALUMINUM ALLOYS SUITABLE FOR AIRPLANE PROPELLERS

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SUMMARY

Laboratory tests were made to obtain information on the load-resisting properties of X76S-T aluminum alloy when subjected to static, impact, and repeated loads. Results are presented from static-load tests of unnotched specimens in tension and in torsion and of notched specimens in tension. Charpy impact values obtained from bend tests on notched specimens and tension impact values for both notched and unnotched specimens tested at several different temperatures are included. The endurance limits obtained from repeated bending fatigue tests made on three different types of testing machine are given for unnotched polished specimens, and the endurance limits of notched specimens subjected to six different ranges of bending stress are also reported.

The results indicated that: (a) polished rectangular specimens had an endurance limit about 30 percent less than that obtained for round specimens; (b) a comparison of endurance limits obtained from tests on three different types of machine indicated that there was no apparent effect of speed of testing on the endurance limit for the range of speeds used (1,750 to 13,000 rpm); (c) the fatigue strength (endurance limit) of the X76S-T alloy was greatly decreased by the presence of a notch in the specimens; (d) no complete fractures of the entire specimens occurred in notched fatigue specimens when subjected to stress cycles for which the mean stress at the notch during the cycle was a compressive stress; for this test condition a microscopic cracking occurred near the root of the notch and was used as a criterion of failure of the specimen; (e) as the mean stress at the notch was decreased from a tensile (+) stress to a compressive (-) stress, it was found that the alternating stress that could be superimposed on the mean stress in the cycle without causing failure of the specimens was increased.

INTRODUCTION

Although the fatigue strengths of most of the commonly used wrought aluminum alloys as determined by laboratory tests of polished specimens are fairly well known, little information seems to be available on the relative notch sensitivity of these alloys, especially for conditions in which the stresses do not occur in completely reversed cycles. For applications of aluminum alloys in service in a member such as a propeller blade, small notches are often produced in the polished surface of the blade by stones being thrown up in the backwash of the propeller during a take-off or when taxying on the field. These notches act as very damaging stress raisers in the member.

The observed stresses in airplane propeller blades have been found to vary over wide ranges in different portions of the blade but usually are stresses of the type that might be represented by a completely reversed alternating stress superimposed on a steady stress in which the steady stress is usually a tensile stress that may be either larger or smaller than the maximum magnitude of the superimposed alternating stress. However, in some cases the significant stresses in a member may occur at a section for which the mean stress in the cycle is a compressive stress; hence, for design purposes, it is necessary to know what maximum alternating stresses may be superimposed on either tensile or compressive mean stresses of various magnitudes without causing failure of the notched member.

The main purpose of the tests herein reported was to determine the flexural fatigue strengths of notched specimens of an aluminum alloy, designated X76S-T, when subjected to six different ranges of stress in ordinary laboratory fatigue tests and to compare these values with the fatigue strengths of polished (unnotched) specimens without abrupt change in section. The alloy X76S-T was thought to be well adapted for use in airplane propeller blades. For more complete information on the other mechanical properties of this metal, tests were also made to obtain the ordinarily determined static and impact properties. It is planned to extend the program of tests to include the aluminum alloy 25S-T, which is also a high-strength alloy used for airplane propeller blades.

The tests herein reported were made in cooperation with the Hamilton Standard Propeller Division of United Aircraft Corporation, which company procured the material for test and machined most of the specimens. Funds were supplied by the National Advisory Committee for Aeronautics to cover the cost of making the tests.

MATERIAL AND METHODS OF TESTING

Types of test.- Three types of test were made on X76S-T aluminum alloy to determine the ordinary mechanical properties of the material as well as the fatigue strengths. These tests may be outlined as follows:

1. Static tests were made of notched and unnotched tensile specimens and of unnotched torsion specimens to determine the strength, the stiffness, and the ductility of the metal. The term "unnotched" will be used throughout this report to designate specimens without an abrupt change of section in the portion under test.

2. Impact tests were made of notched and unnotched tensile specimens and of standard notched Charpy bending impact specimens, at ordinary room temperatures and at low temperatures, to give some indication of the relative notch sensitivity of the material under suddenly applied loads.

3. Repeated load (fatigue) tests were made in three types of testing machine, namely: (a) High-speed rotating cantilever beam fatigue machines using (small) 0.140-inch-diameter round specimens; (b) Krouse rotating cantilever beam fatigue machines using specimens 0.26 inch in diameter; and (c) Krouse flat-plate fatigue machines that subjected both round and rectangular specimens to a vibratory bending action without rotating the test piece. Both notched and unnotched specimens were tested in the vibratory bending and the Krouse cantilever beam fatigue machines; whereas the high-speed rotating-beam machines have been used only to determine the endurance limits of polished specimens.

4. Material and test specimens.- The aluminum alloy tested was originally designated M-68 and is now sold as X76S-T. The chemical composition of this alloy is as follows:

	Percent
Copper	0.6
Zinc	7.6
Magnesium	1.6
Manganese	.5
Titanium	.1
Iron	.5
Silicon	.25
Aluminum	balance

All specimens tested were from the same heat of metal that was reduced, by the latest methods of processing, to bars 1 inch square, which were subsequently swaged in a pair of swaging dies to 1 inch diameter round. The bars were then given a solution and precipitation hardening heat treatment by holding for 10 hours at 860° F, quenching in water, and aging for 12 hours at 275° F.

The details of the specimens used for the ordinary static tensile tests to determine the physical properties of the unnotched specimens are shown in figure 1(a), and the type of notched specimen used in the static tensile test is shown in figure 1(b). Three specimens of each of these two types were tested in an Amsler hydraulic universal testing machine having a capacity of 50,000 pounds. Additional tests were also made on tensile specimens having the same nominal diameter as that in figure 1(a) but having an over-all length of about $9\frac{1}{2}$ inches so that a 6-inch gage length could be employed. The original bars as received were too short to allow the machining of a satisfactory specimen of the more standard 8-inch gage length, and it was deemed desirable to test specimens with a longer gage length to obtain a more accurate value for modulus of elasticity of the alloy.

In figure 1(c) is shown the type of specimen used to determine the static torsional properties of the material. The tension impact specimen shown in figure 2(a) was polished with No. 00 emery paper and the diameter of the specimen near the center was reduced about 0.005 inch less than at the ends to insure breaking in the 2-inch gage lengths.

The notched tensile impact specimen shown in figure 2(b) contained a notch machined with a carefully ground tool that was checked for accuracy of shape by examining in a metallurgical microscope at 100X. This notched impact specimen was geometrically similar to that of the notched static tensile specimen in figure 1(b). The notched bending specimen used was the standard Charpy impact specimen of the dimensions shown in figure 2(c).

The types of specimen used in the rotating-beam fatigue machines are shown in figure 3 and those tested in the vibratory bending fatigue machines are shown in figure 4. The specimens without abrupt change of section (3(a), 3(b), 4(a), 4(b)) were all polished longitudinally with No. 00 emery paper and oil to remove tool marks and circumferential scratches before testing. All these specimens were polished by one man to assure uniformity in the polishing operations. The notched specimens (3(c) and 4(c) were cut with carefully ground tools to assure uniformity in depth, angle of the V-notch, and radius at the root of the notch on all specimens tested. Three faces of the notched specimen in figure 4(c) were polished longitudinally; the root of the notch and the face containing the notch were left in the original machined condition.

The nominal stress in all fatigue specimens was calculated by using the ordinary flexure formula, $s = Mc/I$, in which s is the flexural unit stress (lb/sq in.), M is the bending moment at the critical test section (in.-lb), c is half the depth of the specimen (in.), and I is the moment of inertia of the net cross-sectional area (in.). For the specimens containing notches, the values of stress given in this report are those at the root of the notch computed by the foregoing formula using the values of c and I for the minimum cross-sectional area.

The tests of rotating-beam fatigue specimens were made in two Krouse, 120 inch-pound capacity, cantilever machines of the type shown in figure 5, which were operated at 6000 rpm. Also employed were three small high-speed cantilever beam machines of the type shown in figure 6 that were run at 13,000 rpm.

The vibratory bending fatigue tests were made in six

Krouse flat-plate fatigue machines of the type shown in figure 7. In the operation of those machines the specimen is clamped in the vise V with the clamp C and the pin P removed. Dead weights required to produce the desired stresses are then suspended from the beam at P, and the deflections of the beam are read on the dial D. The clamp C and the pin P are then replaced; the eccentric cam E is adjusted to give the desired alternating part of the load; and the vise is adjusted by moving vertically with the adjusting nuts N to produce the required superimposed steady part of the load. The final adjustment is obtained and the motor is started after the maximum and minimum readings of the dial D correspond to those obtained by using dead weights. During a test this calibration for stress was periodically repeated to prevent change of stress due to wear or loosening of grips, but usually only small adjustments were found necessary during the progress of the tests.

RESULTS OF TESTS

Static tests.- Lower portions of the tensile stress-strain curves for three unnotched specimens of X76S-T aluminum alloy are shown in figure 8, and a typical complete stress-strain diagram is shown in figure 9. The results of these three static tensile tests on a 2-inch gage length and three tests on a 6-inch gage length are tabulated in table I. The tensile tests were carried out in accordance with reference 1. It was at first suspected that perhaps the exceptionally high ratio of yield strength to ultimate strength (see last column of table I) may have been due to a cold working of the metal subsequent to the original heat treatment. However, several bars of the alloy were given a heat treatment to remove any effects of cold working, and the average results of several tensile tests on those treated bars gave values almost identical with those for the specimens listed in table I. The heat treatment consisted of heating 4 hours at 600° F and cooling in the furnace, heating 10 hours at 860° F, quenching in water, and aging 12 hours at 260° F.

The average value of modulus of elasticity for all tensile specimens tested was about 9,700,000 pounds per square inch. This value may be somewhat too low, however, since the 2-inch gage lengths used on some of the specimens are too short to obtain accurate results. A more accurate value would perhaps be obtained by using the average value 9,790,000 pounds per square inch for the three specimens tested on a 6-inch gage length.

The Brinell hardness of the X76S-T alloy tested averaged about 146 (using 500 kg load and 10 mm ball). This value is much higher than the hardness of the other precipitation hardening aluminum alloys, which usually range from about 100 to 130 in Brinell hardness.

The greater portions of the tensile stress-strain curves for notched specimens are shown in figure 10, and the results of these three individual tests are listed in table II. A set of average values obtained from previous tensile tests of notched specimens of a structural steel are shown in the last column of table II for comparison with the values obtained for X76S-T alloy. It will be noted that the relative ratios of strengths obtained for each material are of approximately the same magnitude except for the higher ratio of yield strength to ultimate strength exhibited by the aluminum alloy. The introduction of a notch in specimens of the aluminum alloy also caused a much greater proportionate loss in percentage elongation than did a notch (of sharper radius) in specimens of structural steel.

Static torsion tests were made of three solid specimens (of the type shown in fig. 1(c)) and the lower portions of the torque-angle of twist curves for these tests are shown in figure 11. The instrument used in these tests did not have sufficient travel to continue readings to relatively high angles of twist and therefore it was impossible to determine the yield strengths of these specimens for very large amounts of offset. Hence the yield strengths have been determined for 0.05 percent offset and these values, together with the other commonly determined physical strength properties of the specimens tested in torsion, are listed in table III. For comparison with these values the yield strengths of the specimens tested in static tension were also determined for 0.05 percent offset as well as for the more commonly used value of 0.2 percent offset. It will be observed from the data shown in tables I and III that this metal has very high yield strengths in comparison with its ultimate tensile strength or torsional modulus of rupture and that the numerical value of the ultimate tensile strength of this material is somewhat higher than is usually obtained for heat-treated specimens of most of the commonly used wrought-aluminum alloys.

Impact tests.- The tensile impact tests were made in a standard Charpy machine having a capacity of 223 foot-pounds by employing special auxiliary specimen grips containing spherical seats that were designed to minimize bending or eccentric loading on the specimen during test. Tensile impact tests were made both at room temperature 71° F and at a low temperature (-40° F) since it was felt that any change in properties of the metal which would be induced by low temperatures would be of importance.

Cooling of the specimen to the low temperature was accomplished by immersing the pendulum, the test specimen, and the attached holders in a bath of acetone contained in a special insulated box. The entire bath was cooled by adding dry ice until the desired temperature was obtained and the bath was then maintained at this temperature for at least 5 minutes before testing the specimen. Previous calibration tests in which readings were taken on several thermocouples attached to a specimen indicated that this interval of time was sufficient for these small specimens to reach a uniform temperature equal to that of the bath. In the performance of the actual test of the specimen only about a 4-second time interval elapsed between the removal of the box containing the coolant and the actual fracturing of the specimen; hence it was felt that the temperature of the specimen did not change appreciably while testing since it was surrounded by relatively heavy masses of metal cooled to the same temperature as the bath.

The test data showing the energy required to rupture each specimen tested and the average values obtained for each group of specimens are shown in table IV for the tests at 71° F and in table V for the tests at -40° F. For purposes of comparison one may regard the energy required to rupture the unnotched specimens (column 3) as indicative of the impact strength, and the percentage of elongation and reduction of area (columns 6 and 9) as measures of the ductility of the material under these conditions of testing. A comparison of the values obtained for notched specimens with those for unnotched specimens (see columns 5 and 8) gives a rough measure of the notch sensitivity of the metal under rapid loading; it should be noted, however, that the notched specimens of X76S-T alloy had a smaller minimum diameter than the unnotched specimens and hence would be expected to have a somewhat smaller strength.

For a rough comparison with the values for X76S-T alloy listed in table IV, there is included a set of data on ordinary structural steel tested under similar conditions. If allowance is made for the fact that the unnotched steel specimens were somewhat smaller in diameter than those for the X76S-T alloy, it may be seen that the steel required considerably more energy to rupture than did the aluminum-alloy specimens though the relative ratio of energy absorbed by the notched specimens as compared with that for the unnotched specimens (listed in column 5) would probably be about the same for these two metals if the same size specimens had been used.

The average energy absorbed by <u>all</u> specimens tested at -40° F (see column 3 of table V) is below that for the specimens tested at 71° F; however, the first two specimens in column 3 show an abnormally low value of energy absorption probably caused by their breaking at the end of the gage length. If these two specimens are omitted from the average, this value becomes slightly greater than the average obtained for the specimens tested at room temperature. A comparison of the average values listed in tables IV and V therefore leads to the conclusion that the aluminum alloy exhibited practically the same strength, ductility, and notch sensitivity in the tensile impact tests at -40° F as it did at room temperature.

The results of a series of notched bar Charpy <u>bending</u> tests at temperatures ranging from 72° F to -70° F are shown in table VI. Here again the X76S-T alloy exhibited practically the same energy-absorbing capacity at low temperatures as it did at room temperatures. There was a slightly greater energy absorption by the specimens tested at -40° F than for the other temperatures of the test, but no significant decrease in resistance to the suddenly applied load was obtained as the temperature was dropped over the 142° F range below room temperature.

<u>Repeated load tests for completely reversed bending</u>.- The results of the rotating-beam fatigue tests of unnotched specimens of the X76S-T alloy are shown in the S-N curves of figure 12 on which are plotted the data obtained from tests on two different types of machine. These tests were made at two different rates of stressing, namely, 13,000 and 6,000 completely reversed cycles of stress per minute. For comparison with these values figure 13 shows the results of tests in the vibratory bending-fatigue machines of round, square, and rectangular specimens that were subjected to 1,750 completely reversed cycles of stress per minute. The "square" specimens tested were of the same

general contour and dimensions as the "round" specimen shown in figure 4(b) except that the reduced portion was milled flat on four sides with a 3-inch radius cutter leaving the test section square in cross section. The endurance limits of these two groups of unnotched polished specimens have been scaled as the ordinates to the S-N curves at one million, ten million, and one hundred million completely reversed cycles of stress and are listed in table VII.

The vibratory bending tests have been carried out to 100 million cycles of stress and it is felt that the endurance limits based on 500 million cycles of stress would be only slightly smaller than those listed in the last column of table VII; the data shown in figure 12 indicate that the S-N curves flatten out, tending to approach a horizontal asymptote with only a small difference in the ordinates to the curve at 100 or 500 million cycles of stress. Figure 14 is a photograph of the test sections of the four types of specimen tested in the vibratory bending machines and shows the fatigue fractures obtained as well as the relative shapes of the specimens.

It will be observed that the endurance limits tabulated for the square and for the rectangular specimens in table VII are considerably lower than the values obtained for round specimens in either the rotating-beam or the vibratory bending-fatigue machines. It is felt that this important difference may be mainly attributed to the effects of the shape of the cross section on the strength of the member and that it is not caused by faulty characteristics of machines or variations in the speed of testing. No complete explanation for this variation in endurance limit between round and rectangular specimens is known at the present time, but it seems probable that the following five factors may possibly lead to variations in the fatigue-strength obtained for different types of specimen.

1. Variations in the amount and direction of the cold working and of the residual stresses developed in the surface fibers by differences in the machining operations used in shaping the specimen.

2. Differences in the amount of material in the specimen that is subjected to the maximum or peak stress at any one instant and the relative steepness of the stress gradient in the region of this peak stress.

3. Variations of stress across the width of the beam. This variation may be occasioned by the wide beam acting as a slab subjected to a three-dimensional stress system or may be caused by localized concentrations of stress at the sharp outward projecting corners where a slight roughness of the polished edges would lead to a premature fatigue fracture.

4. Faulty alinement of machines that would produce additional stresses of varying amounts depending upon the shape and size of specimen tested.

5. Variations in properties of the metal between the center and outside surface of the original bar stock from which specimens were cut.

It was found that most of the fatigue fractures in the rectangular specimens started at the corners, which indicates that item 3 or item 5 may have been most important in causing the rectangular specimens to appear to have a lower fatigue strength. Item 4 probably was not of importance in these tests because the only faulty alinements that could exist would produce either a small torsional twisting of the specimen or an unsymmetrical bending in which the plane of the applied loading made some small angle with the longitudinal plane of symmetry of the specimen. If a twisting of the specimen existed, there would be developed shearing stresses on the cross section that reach a maximum value at the center of the long face of the rectangular specimen and are zero at the corners where most of the failures started. Similarly, a simple computation showed that the plane of loading would have to vary from the assumed plane in which the loads were supposedly applied by 10° to produce only about a 5-percent increase in stress due to unsymmetrical bending of the wide rectangular specimens, and even this angularity was much greater than that which existed in the machines.

A computation to determine possible increases of stress due to inertia effects of the oscillating specimen indicated that this effect added less than about 2 percent to the maximum stress and would not be appreciably different for the round as compared with the rectangular specimens. Consequently, since the endurance limit of the rectangular specimens was about 30 percent less than that of the round specimens tested in the same machines, it is not probable that small irregularities in the fatigue-testing machines could have accounted for this great difference, especially since the specimens tested for any one endurance limit were used interchangeably on six different machines of the same type.

In the lower portion of figure 13 is plotted the S-N curve for the rectangular specimens with a V-notch tested under completely reversed cycles of flexural stress. The great reduction of strength of the specimens caused by the introduction of the notch is quite apparent by the difference in ordinates to the curves shown in this figure. The ordinates were scaled at 100 million cycles of stress; the values of the endurance limits were thus obtained as 16,500 pounds per square inch for the rectangular unnotched specimens and only about 7,500 pounds per square inch for the notched specimens. By the use of the ratio of these two endurance limits as a measure of the factor of stress concentration k caused by the notch, a value of $k = 2.20$ is found. If this calculation is based on the endurance limit of the round specimens (24,000 lb/sq in.) a value of $k = 3.20$ is obtained.

In figure 15 is shown the S-N curve for rotating-beam specimens containing a V-notch similar to that used in the vibratory bending specimens. In this case the endurance limit at 100 million cycles of stress is about 9,000 pounds per square inch (slightly higher than for the vibratory bending tests), and giving a value of $k = 2.44$ when compared with the endurance limit of 22,000 pounds per square inch for the unnotched specimens tested in the same machine.

Effects of range of stress on endurance limits of notched specimens.- In order to study the effect of range of stress on the endurance limit of specimens with a V-notch, tests were made in the vibratory bending machines with specimens subjected to a mean or steady stress on which was superimposed a completely reversed alternating stress. Six different endurance limits were determined corresponding to three different ranges in which the mean stress at the root of the notch was a tensile stress, two ranges in which the mean stress was a compressive stress, and one range in which the mean stress was zero (completely reversed stress cycle).

The S-N curves for stress cycles in which the mean stress at the notch was a tensile stress are shown in figure 16, and the S-N curve for the completely reversed stress cycle is shown in the lower portion of figure 13.

The endurance limits for these four stress cycles have been obtained by scaling the ordinates to the S-N curves at 100 million cycles of stress and these values are shown in table VIII.

For the two ranges in which the mean or steady stress at the notch was a compressive stress, the specimens developed cracks at the root of the notch but did not completely fracture even though subjected to a large number of cycles of superimposed alternating stress with a total range (double amplitude) of as much as 30,000 pounds per square inch. Photographs of some of these cracks showing views looking down into the notch are presented in figure 17, and views of cracks in the side face of the specimens at the notch are shown in figure 18. The small dark areas in these figures are regions where small pieces of metal have cracked out and spalled off, but this spalling occurred only for specimens tested at relatively high stresses. For specimens tested at lower stresses the cracks formed were very small and could not be seen without the aid of a low-power microscope. Hence the fatigue test data could not be interpreted in the usual manner by plotting S-N diagrams, and no definite indications of failure of a specimen were evident except for the microscopic cracking at the notch; it was also difficult to determine with any accuracy the number of cycles of stress required to start the formation of cracking. Consequently, it was decided to assume arbitrarily that cracks which could be seen with a 40X microscope constituted failure of a specimen. The endurance limits were obtained by testing groups of about eight specimens at different stresses usually varying by 1000-pounds-per-square-inch increments and determining the maximum stresses that could be repeated 100 million times without causing a cracking at the notch that would be visible with the 40X microscope. The values of endurance limit determined in this manner for the two compressive stress cycles are listed in table VIII.

The effect of the range of stress on the endurance limits of the V-notch specimens is illustrated in the Goodman-type diagram of figure 19 on which are plotted the data of table VIII. On this diagram the ordinates represent the minimum stress (S_{min}) and the maximum stress (S_{max}) of the stress cycle and the abscissas represent the corresponding mean stress (algebraic average of S_{min} and S_{max}). For any given mean stress the algebraic difference between S_{max} and S_{min} represents the total range or double amplitude of the superimposed alternating stress that will cause failure after approximately 100 million cycles of stress.

It will be observed that, as the algebraic value of the mean stress in the cycle was decreased from a large tensile (+) stress to zero and thence to a compressive (-) stress, an appreciable increase occurred in the total alternating range of stress required to cause failure. This result is shown more definitely by the curve in figure 20 in which the ordinates indicate the total alternating stress range $(S_{max} - S_{min})$ and the abscissas represent the corresponding mean stress in each style.

Considering these data and the fact that no fractures occurred in the specimens tested with compressive mean stresses at the notch, it is evident that this aluminum alloy can withstand considerably greater magnitudes of superimposed alternating stresses when the mean stress is decreased from a tensile to a compressive stress.

DISCUSSION OF RESULTS

One of the most striking results of the tests is the fact that carefully polished rectangular specimens of the X76S-T alloy exhibited an endurance limit about 30 percent less than the values obtained from polished round specimens tested in three different types of machine: Somewhat similar results also indicating that the shape of cross section of a test specimen affects its fatigue strength were recently indicated in data included in reference 2. In this report specimens of rectangular cross section gave values of flexural fatigue-endurance limits of two steels that ranged from 0 to 11,000 pounds per square inch lower than those obtained from specimens of circular cross section. These differences were noted when comparing the results of four individual tests of the same two billets of steel.

Perhaps one reason for the apparent weakness of the rectangular specimens is the fact that the sharp outward projecting corners are inherently weak because they are difficult to polish without leaving minute cross scratches or feathered edges that offer convenient nuclei from which a fatigue fracture may readily start. The data obtained from the tests of unnotched rectangular specimens showed considerably more scatter when plotted on the S-N curve of figure 13 than did the test results for the other types of specimen. Perhaps this result may have been caused by slight variations in the roughness of the sharp projecting corners since most of the rectangular specimens failed with a fracture starting at a corner.

In order to test this hypothesis three rectangular specimens were modified by rounding off the corners to a radius of approximately one-sixteenth inch and polishing carefully in a longitudinal direction. One specimen was then tested in completely reversed bending at a stress of 22,000 pounds per square inch and ran more than 100 million cycles of stress without fracture. A comparison of this specimen with the data plotted for the rectangular unnotched specimens in figure 13 shows that a considerable increase of life was obtained by rounding off the corners.

The other two specimens were tested at 25,000 and 26,000 pounds per square inch and failed at about 300,000 cycles of stress, which was slightly short of the normal S-N curve for the rectangular specimens. This scatter of data for all rectangular specimens tested indicates that there may have been some mechanical defects (such as inclusions or residual stresses) near the surface of the original bar stock that had a tendency to decrease the fatigue strength of the (larger) rectangular specimens.

A comparison of the endurance limits of the round specimens (last column, table VII) indicates little or no effect of speed of testing within the range of speeds (from 1,750 to 13,000 rpm) used in the tests. The difference in numerical values of the endurance limits may be accounted for by small differences in the behavior of the three types of testing machine and by slight variations in different bars of the same metal; however, there is always a possibility that a slight change in endurance limit of the metal that might result from a change in speed of testing may have been offset by a change in characteristics of one of the testing machines.

It is important to note that the alloy X76S-T is much stronger in static tension and has a higher flexural fatigue strength than the other commonly used aluminum alloys. However, the alloy exhibited a fairly high notch sensitivity as determined by the reduction of fatigue strength of notched specimens below that of the polished unnotched specimens. When subjected to a service condition such as that in an airplane propeller, where the face of the blade is often scratched or notched by stones thrown up during a take-off, the fatigue strength of the metal in a notched condition is of primary importance. It is quite possible that notched specimens of some of the other aluminum alloys may exhibit fatigue strengths comparable with those obtained for notched specimens of X76S-T alloy even though the X76S-T alloy appears to have a considerably higher fatigue strength when a comparison is made on the basis of results obtained from polished unnotched specimens. It is planned to repeat this series of tests with the aluminum alloy 25S-T so that a closer comparison of their relative notch sensitivity and the relative effect of range of stress on notched specimens can be obtained.

In general, the results of the fatigue tests with notched specimens indicated that the metal could withstand a greater alternating stress range without the formation of fatigue cracks when the mean stress in the cycle was changed from a tensile to a compressive stress. In addition, the fatigue cracks developed at the root of a notch did not spread rapidly when the mean stress was compressive and no complete fractures of the specimens were obtained even when stresses somewhat above those required to produce cracking were repeated 100 million times. Thus, if a notched member were designed to operate with the mean stress (at the notch) a compressive stress - an additional factor of safety against complete fracture - would exist; any fatigue cracking at the notch could probably be detected by periodical inspections long before the cracking had developed to a dangerous extent.

For example, if the areas of a propeller blade that are most likely to be nicked or scratched in service could be designed to operate with a compressive mean stress on which is superimposed the flexural vibrations that normally occur in flight, it is probable that the blade would offer greater resistance to the formation of fatigue cracks caused by the vibrations; furthermore, even if cracks did form in these areas they would develop relatively slowly and would be readily visible long before complete fracture of the blade was imminent.

CONCLUSIONS

The following general conclusions from this series of mechanical tests on X76S-T aluminum alloy seem justified:

1. The static, elastic, and ultimate tensile strengths and the Brinell hardness of X76S-T alloy are higher than those of the other commonly used aluminum alloys.

2. The alloy has a ductility and a stiffness that are only slightly smaller than those of the other strong aluminum alloys, such as 25S-T.

3. The tensile yield strength of X76S-T is very high in relation to its ultimate strength (approximately 0.9 of the ultimate); whereas, for other aluminum alloys, it is a much lower proportion of the ultimate strength (about 0.6 for the case of 25S-T).

4. Tension impact tests of notched and unnotched specimens at -40° F and tests of Charpy notched bar bending specimens at temperatures down to -70° F indicated that the ductility and the energy-absorbing properties of the metal were not materially affected by a large drop in the temperature of testing below room temperature.

5. V-notches with 0.01 inch radius at the root caused large decreases in elongation in 2 inches and in the energy required for rupture in the tension impact tests.

6. The flexural fatigue endurance limits of polished (unnotched) specimens when subjected to completely reversed stress cycles were found to vary as the shape of cross section of the specimen was changed. Tests of rectangular specimens gave an endurance limit about 30 percent less than that obtained for round specimens tested in the same machine.

7. Tests of polished rotating-beam specimens in two different machines gave endurance limits of 21,000 and 22,000 pounds per square inch, respectively, when based on 500 million cycles of stress. These values are somewhat higher than the endurance limits of most other aluminum alloys.

8. Tests of polished specimens on three different machines operating at different speeds gave endurance limits ranging from 22,000 to 24,000 pounds per square inch at 100 million cycles of stress. Hence there was no appreciable change in the endurance limit under these test conditions as the speed of testing was varied from 1,750 to 13,000 rpm.

9. The introduction of a V-notch in the test section

decreased the fatigue strength of the alloy for completely reversed cycles of stress to only 31 to 41 percent of the strength of polished round specimens, depending somewhat on the shape of the member tested.

10. As the mean or steady stress at the notch was decreased from a tensile (+) stress to a compressive (-) stress, the total alternating range of stress that could be resisted by the notched specimens without causing failure gradually increased from a range of 9,000 pounds per square inch for a tensile mean stress of 14,500 pounds per square inch to a range of 17,000 pounds per square inch for a compressive mean stress of 8,500 pounds per square inch.

11. The notched specimens tested with an alternating stress superimposed on a steady compressive stress offered a greater factor of safety against complete fracture than for the other stress cycles investigated. The endurance limits for the specimens tested in the compressive ranges were based only on a microscopic cracking as a criterion of failure, and the specimens did not fracture even though stresses considerably above these endurance limits were repeated a large number of times.

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Urbana, Illinois, July 25, 1941.

REFERENCES

1. Anon.: Standard Methods for Testing of Metallic Materials. A.S.T.M., E8-36.

2. Moore, H. F.: Report of the Research Committee on Fatigue of Metals. A.S.T.M. Proc., vol. 41, 1941, p. 133.

TABLE I - STATIC TENSION TESTS OF X76S-T ALLOY

[$\frac{1}{2}$-in.-diameter unnotched specimens in fig. 1(a)]

Specimen (a)	Yield strength 0.05% offset	Yield strength 0.2% offset	Ultimate strength (lb/sq in.)	Elongation in 2 in. (percent)	Elongation in 6 in. (percent)	Reduction of area (percent)	Modulus of elasticity (lb/sq in.)	Ratio yield strength (0.05% offset) to tensile strength
E1	62,300	66,000	71,100	18.0	10.7	45.6	9.73×10^6	0.826
E2	64,500	67,400	72,100	17.0	11.8	39.3	9.72×10^6	.895
E3	63,600	67,200	72,600	19.5	11.8	46.1	9.93×10^6	.876
T1	67,000	69,300	74,400	20.0	----	35.5	9.60×10^6	.900
T2	62,000	64,600	71,400	20.0	----	37.8	9.57×10^6	.868
T3	65,500	68,500	73,500	20.5	----	39.5	9.58×10^6	.956
Average	64,200	67,200	72,500	19.2	11.4	40.6	[b]9.69×10	.887

[a]E specimens tested with a 6-in. gage length.
T specimens tested with a 2-in. gage length.

[b]The average modulus of elasticity for the three specimens tested with the 6-in. gage length was 9,790,000 lb/sq in.

TABLE II - STATIC TENSILE TESTS OF NOTCHED SPECIMENS

[Gáge length 2 in. on $\frac{1}{2}$-in.-diameter notched specimens shown in fig. 1(b)]

Specimen	Yield strength (lb/sq in.)		Ratio of yield strength at root of notch to yield strength of unnotched specimens		Ultimate strength (lb/sq in.)	Ratio of tensile strength at root of notch to tensile strength of unnotched specimens	Elongation in 2 in. (percent)	Ratio of elongation of notched specimens to elongation of unnotched specimens	Ratio of yield strength for 0.05% offset to tensile strength (notched specimens)
	0.05% offset	0.2% offset	0.05% offset	0.2% offset					
N13	85,600	93,000	1.32	1.38	97,700	1.34	2.0	0.10	0.876
N14	86,800	94,000	1.34	1.39	97,700	1.34	2.0	.10	.890
N15	82,800	90,600	1.28	1.34	94,700	1.30	1.5	.07	.875
Average	85,066	92,530	1.31	1.37	96,700	1.33	1.83	.09	.880
Structural steel (a)	-------	51,800	-----	1.46	82,100	1.38	10.0	.241	.632

[a] Specimens of same type as those in fig. 1(b), except that a very small radius (sharp corner) was used at the root of the notch.

TABLE III - STATIC TORSION TESTS OF X76S-T ALLOY

[Gage length 2 in. on 0.56-in.-diam. specimen shown in fig. 1(c)]

Specimen	Yield strength 0.05% offset (lb/sq in.)	Modulus of rupture (lb/sq in.)	Modulus of elasticity (lb/sq in.)	Ratio of yield strength to modulus of rupture
S1	39,800	63,800	4.02×10^6	0.623
S2	38,900	62,000	3.97×10^6	.627
S3	39,800	65,000	4.18×10^6	.613
Average	39,500	63,600	4.06×10^6	.621

TABLE IV - TENSION IMPACT TESTS AT 71° F

1	2	3	4	5	6	7	8	9
Specimen		Energy to rupture (ft-lb)		Energy ratio	Elongation in 2 in. (percent)		Elongation ratio	Reduction of area, (percent)
Unnotched	Notched	Unnotched (a)	Notched (b)	(c)	Unnotched	Notched	(d)	Unnotched
7	N7	77.2	7.6	-------	9.0	2.0	-----------	38.0
9	N8	90.9	11.0	-------	13.0	2.0	-----------	30.2
12	N9	94.8	8.1	-------	(e)	1.5	-----------	37.8
A14	--------	75.7	--------	-------	12.0	--------	-----------	35.8
A15	--------	73.2	--------	-------	12.0	--------	-----------	38.6
A16	--------	69.4	--------	-------	11.0	--------	-----------	37.8
Average		80.2	8.9	0.111	11.4	1.8	0.158	36.3
Structural steel		[f]107.5	25.3	0.235	[f]31.5	4.5	0.143	----------

[a]Unnotched specimens are those without abrupt change in section as shown in fig. 2(a).

[b]V-notch specimen as shown in fig. 2(b).

[c]Ratio of energy to rupture notched specimens to energy to rupture unnotched specimens.

[d]Ratio of elongation of notched specimen to elongation of unnotched specimen.

[e]Specimen broke at end of gage length.

[f]Specimens of steel were 0.200-in.-diam. instead of the 0.250-in.-diam. specimens used for X76S-T.

TABLE V - TENSION IMPACT TESTS AT -40° F

1	2	3	4	5	6	7	8	9
Specimen		Energy to rupture (ft-lb)		Energy ratio	Elongation in 2 in. (percent)		Ratio	Reduction of area, (percent)
Unnotched	Notched	Unnotched (a)	Notched (b)	(c)	Unnotched	Notched	(d)	Unnotched
8	N10	[e]38.1	7.3	-------	[e]-------	1.5	-------	36.2
10	N11	[e]36.5	10.1	-------	[e]-------	2.0	-------	38.0
11	N12	94.4	7.3	-------	14.0	2.0	-------	37.7
B14	--------	80.9	--------	-------	12.0	--------	-------	37.3
B15	--------	75.7	--------	-------	11.5	--------	-------	36.4
B16	--------	80.7	--------	-------	11.0	--------	-------	37.2
Average		[f]67.7	8.2	0.121	12.1	1.8	0.149	37.1

[a]Unnotched specimens are those without abrupt change in section as shown in fig. 2(a).

[b]V-notch specimen as shown in fig. 2(b).

[c]Ratio of energy to rupture notched specimens to energy to rupture unnotched specimens.

[d]Ratio of elongation of notched specimen to elongation of unnotched specimen.

[e]Specimen broke at end of gage length.

[f]Omitting specimens 8 and 10, which broke near shouldered ends of specimen, this average energy becomes 82.9 ft-lb.

TABLE VI - CHARPY BENDING TESTS

[Using notched bar specimens shown in fig. 2(c)]

Specimen	Temperature of test (°F)	Energy absorbed (ft-lb)
A7	72	9.1
A8	72	9.6
A9	72	8.6
Average	72	9.1
A12	30	8.9
B7	30	8.8
B10	30	9.6
Average	30	9.1
B8	-40	13.4
B11	-40	11.2
A11	-40	12.3
Average	-40	12.3
B9	-70	8.6
B12	-70	9.1
A10	-70	8.6
Average	-70	8.8

TABLE VII - ENDURANCE LIMITS OF UNNOTCHED SPECIMENS

COMPLETELY REVERSED STRESS CYCLE

[Specimens, without abrupt change in section, of types shown in fig. 3(a), 3(b), and 4(b).]

Machine	Shape of specimen at test section	Depth of specimen at test section (in.)	Endurance limits, (lb/sq in.) for 10^6 cycles	for 10^7 cycles	for 10^8 cycles
Rotating cantilever beam	Round	0.26	33,000	26,500	22,000
Do.------	--do.--	.14	30,000	24,500	22,500
Vibratory bending	--do.--	.26	32,500	27,500	24,000
Do.------	Rectangular	.24	24,000	18,500	16,500
Do.------	Square	.25	24,000	20,000	18,500

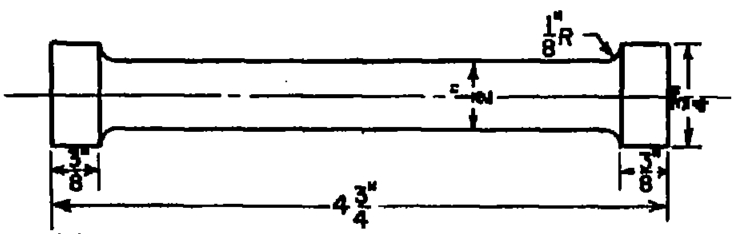
TABLE VIII - EFFECT OF RANGE OF STRESS ON ENDURANCE LIMITS

OF NOTCHED SPECIMENS

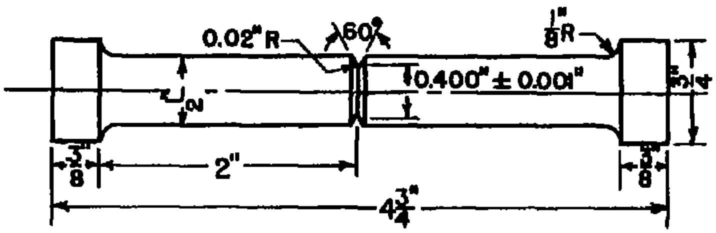
[Based on 100 million cycles of stress,
positive stresses are tension; negative, compression]

Type of stress variation	Maximum stress in cycle, S_{max} (lb/sq in.)	Minimum stress in cycle S_{min} (lb/sq in.)	Mean stress in cycle (lb/sq in.)	Total alternating stress range $S_{max} - S_{min}$ (lb/sq in.)
Zero to max. in compression	0	-17,000	-8,500	17,000
+4,000 lb/sq in. to max. in compression	+4,000	-12,000	-4,000	16,000
Completely reversed	+7,500	-7,500	0	15,000
Zero to max. in tension	+13,000	0	+6,500	13,000
+5,000 lb/sq in. to max. in tension	+16,500	+5,000	+10,750	11,500
+10,000 lb/sq in. to max. in tension	+19,000	+10,000	+14,500	9,000

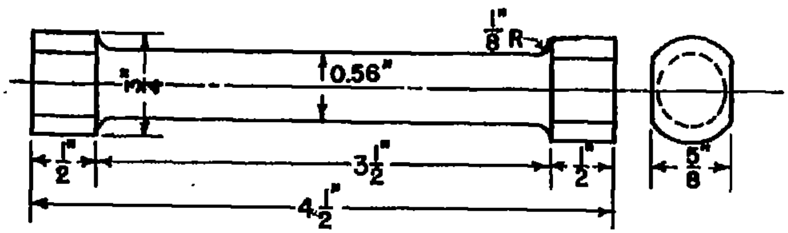
FIG. 1.- SPECIMENS FOR STATIC TESTS.



(a) Static tension - unnotched

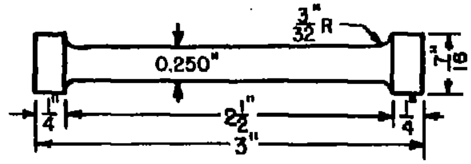


(b) Static tension - notched

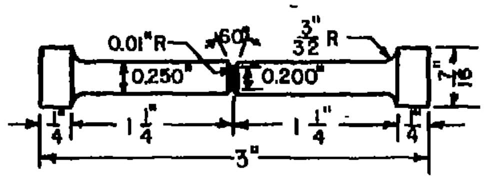


(c) Static torsion

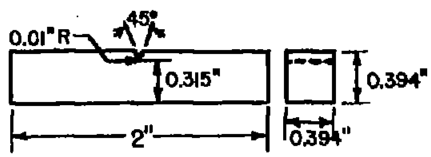
FIG. 2.- SPECIMENS FOR IMPACT TESTS.



(a) Tensile impact - unnotched

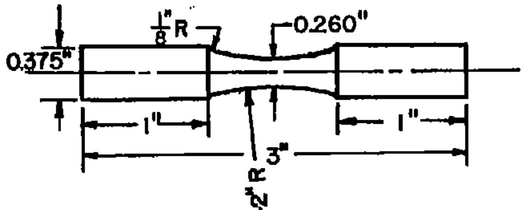


(b) Tensile impact - notched

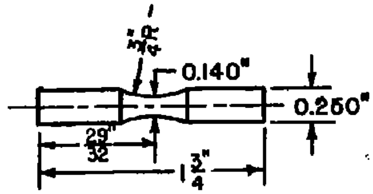


(c) Charpy impact bending

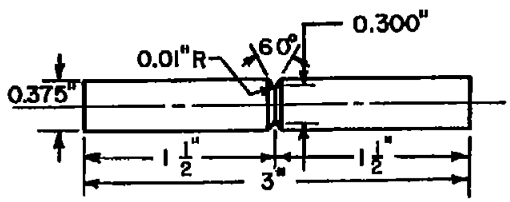
FIG. 3.- SPECIMENS FOR ROTATING-BEAM FATIGUE MACHINES.



(a) Unnotched specimen

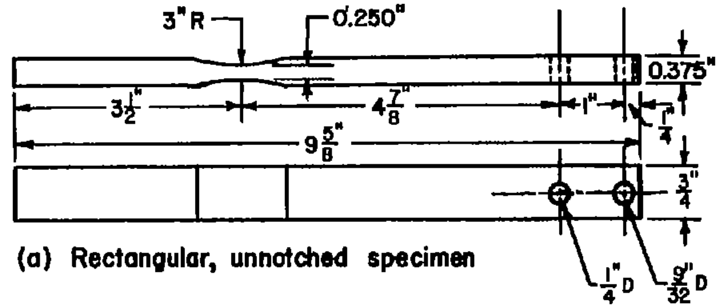


(b) Small, unnotched specimen

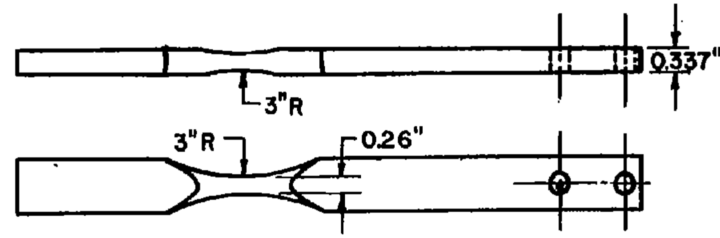


(c) Notched specimen

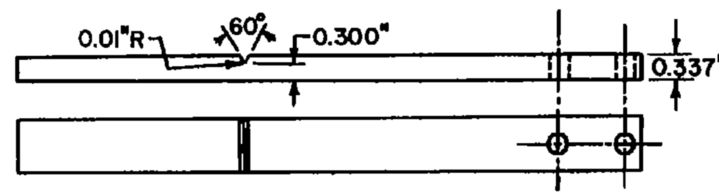
FIG. 4.- SPECIMENS FOR VIBRATORY BENDING FATIGUE MACHINES.



(a) Rectangular, unnotched specimen



(b) Round, unnotched specimen



(c) Rectangular, notched specimen

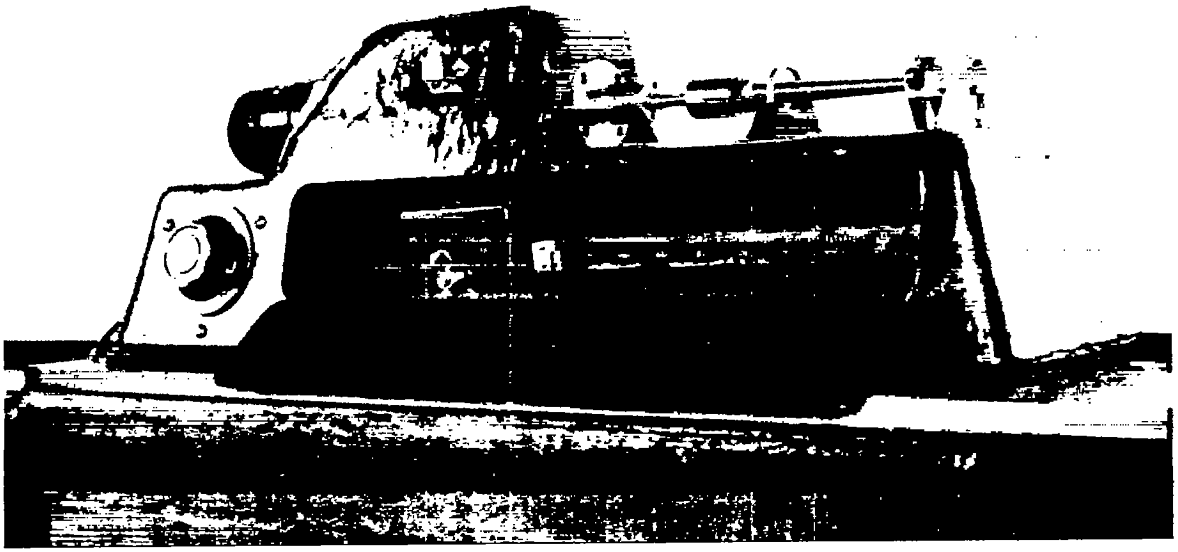


Figure 5.- Krouse rotating cantilever beam fatigue testing machine.

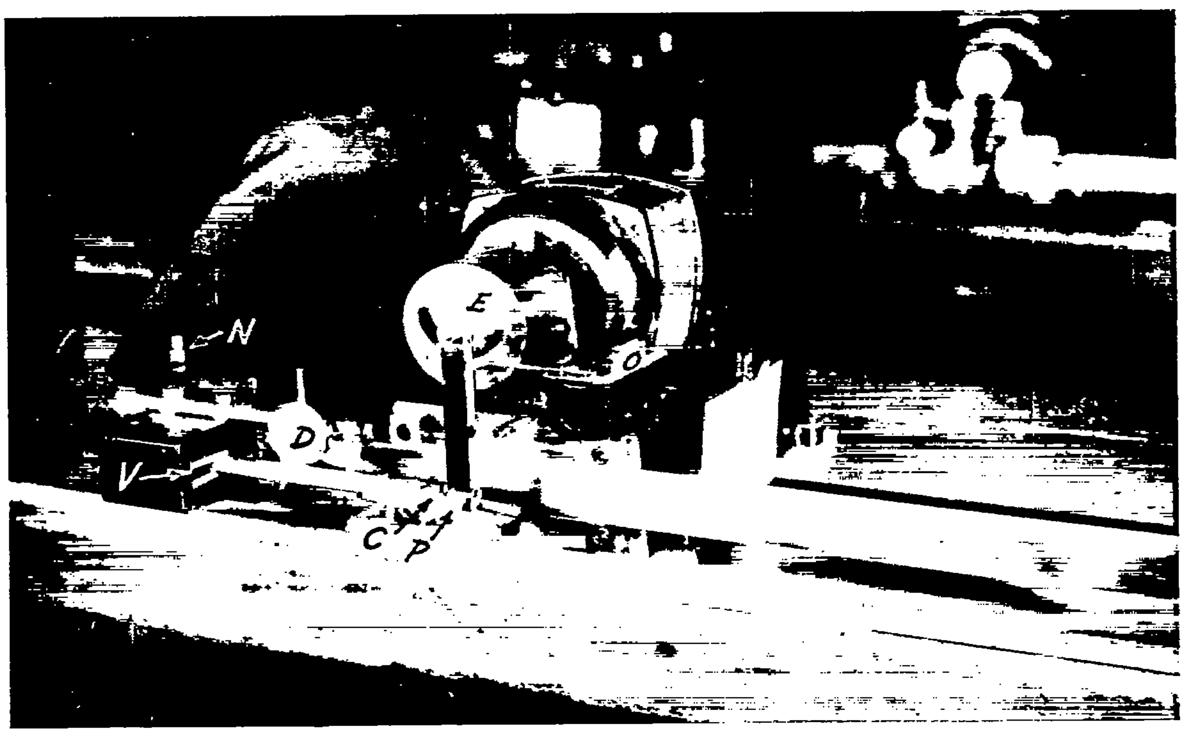


Figure 7.- Krouse flat plate fatigue testing machine.

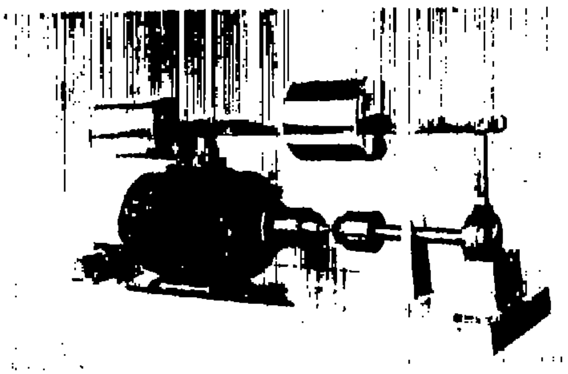


Figure 6.- Small high-speed cantilever beam fatigue testing machine.

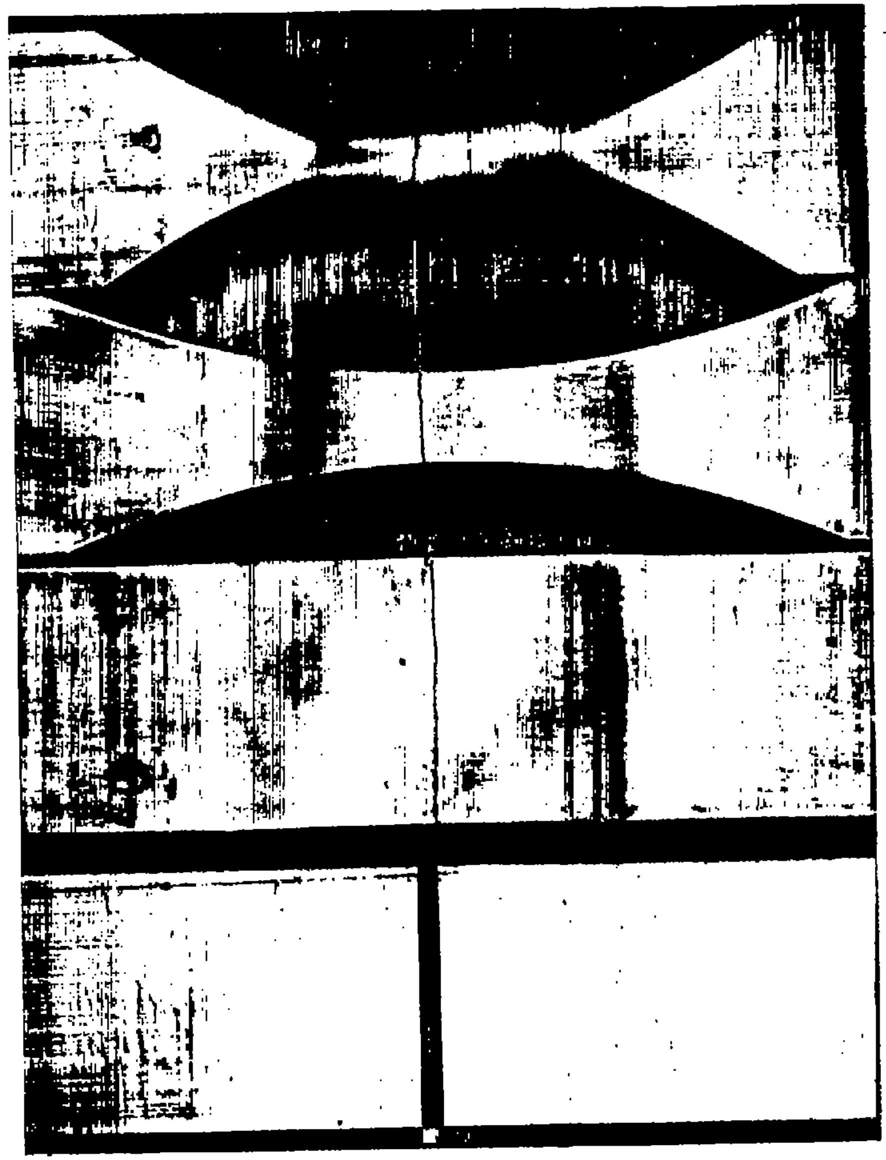


Figure 14.- Fractured vibratory bending test specimens

FIG. 8.- STATIC TENSILE TESTS — X76S-T ALLOY.

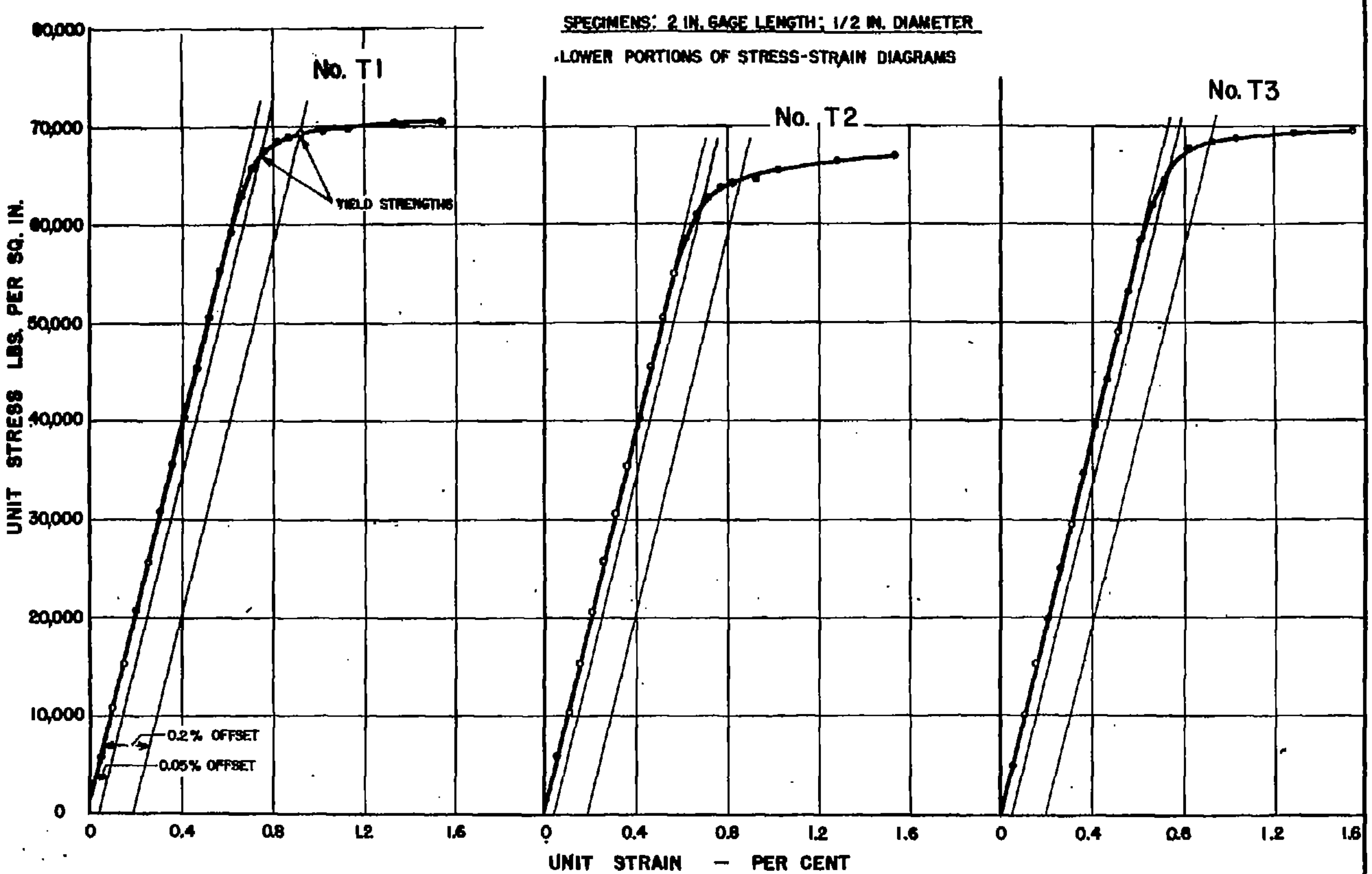


FIG. 9.-TENSILE TEST - X76S-T ALLOY.

SPECIMEN No. T1

2 IN. GAGE LENGTH - 1/2 IN. DIAM.

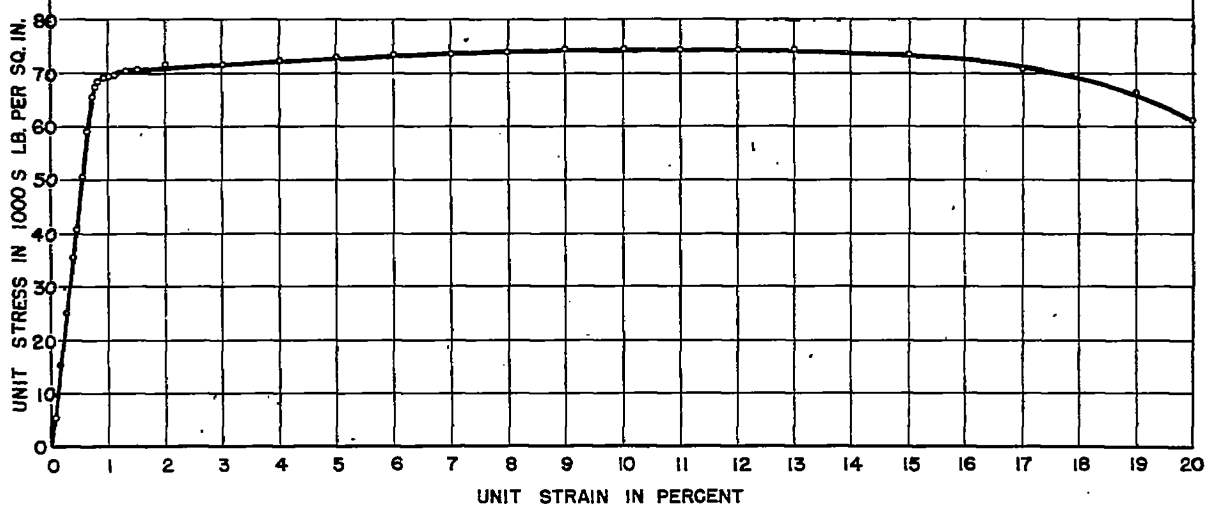
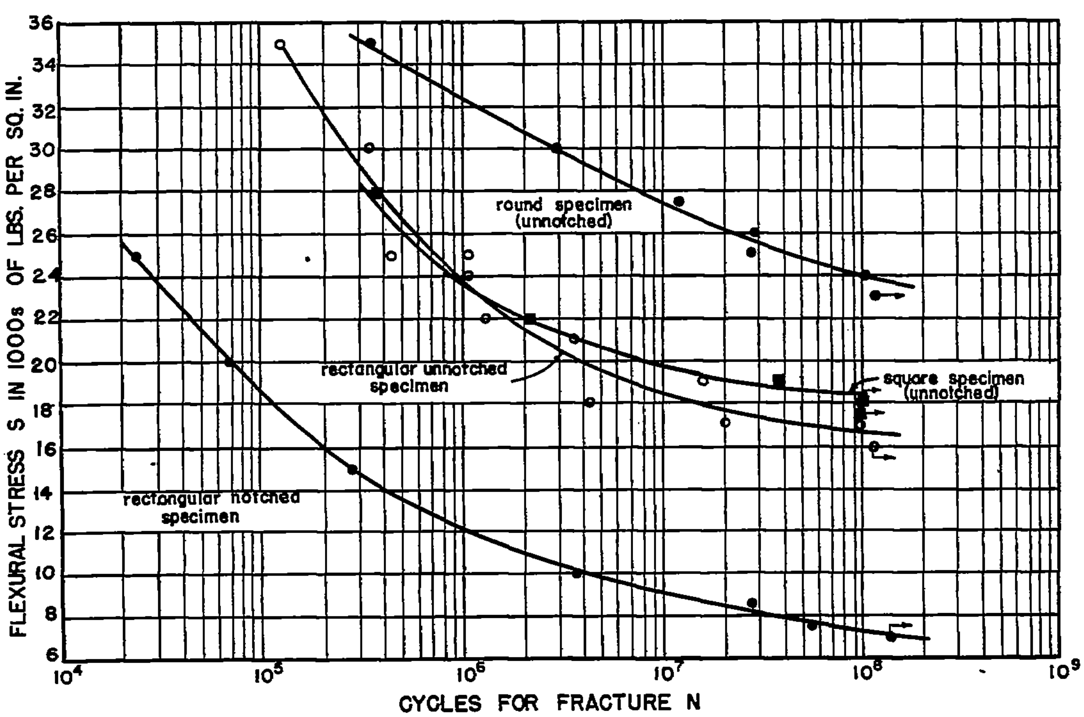


FIG. 13.-
VIBRATORY BENDING FATIGUE TESTS OF X76S-T ALLOY.
Completely Reversed Stress Cycle



●→ indicates specimen did not fail

FIG. 10.- STATIC TENSILE TESTS OF NOTCHED SPECIMENS OF X76S-T ALLOY.

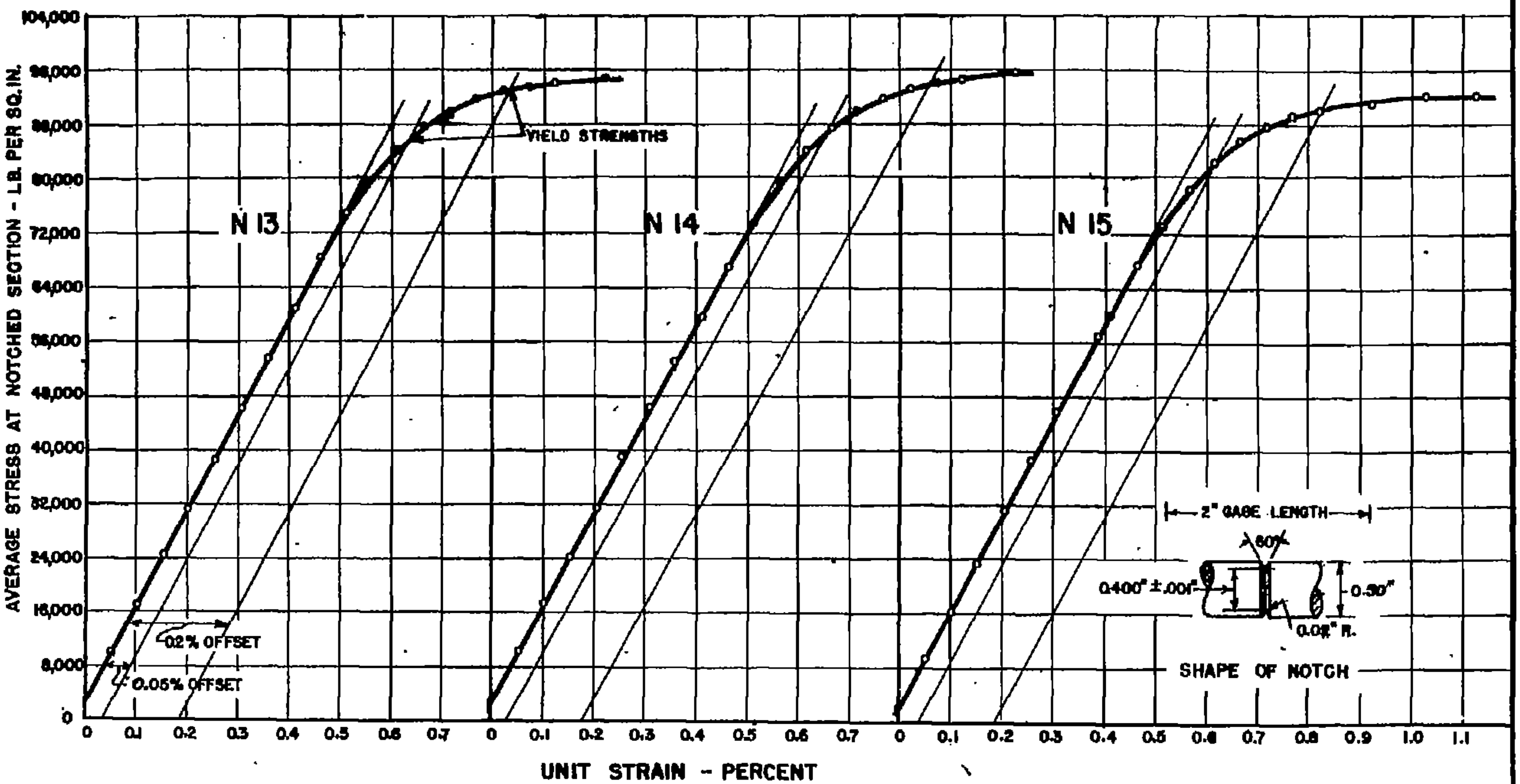


FIG. 11.- STATIC TORSION TESTS - X76S-T ALLOY.

SPECIMENS: 2 IN. GAGE LENGTH; 0.56 IN. DIAMETER

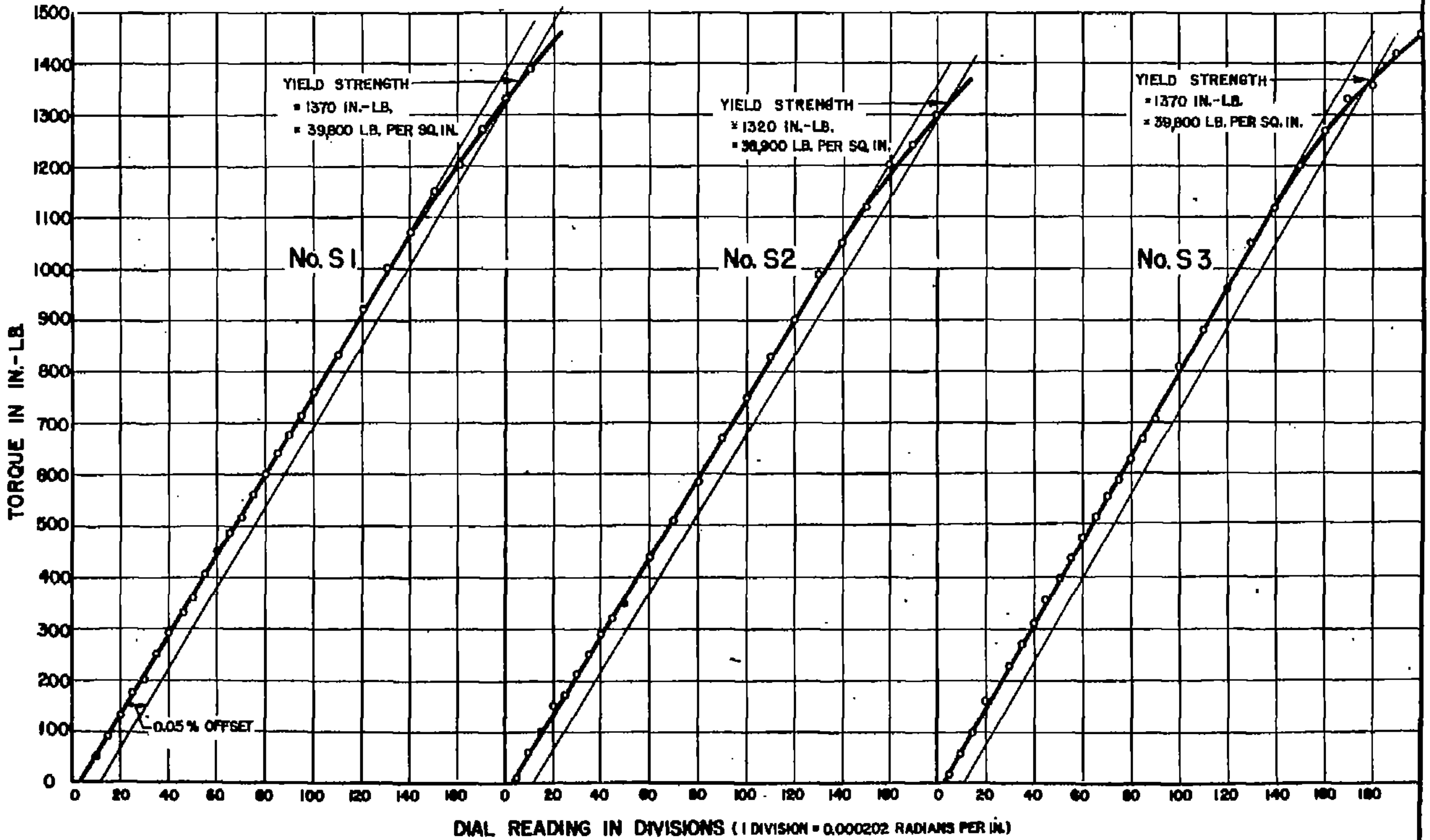


FIG. 12.- ROTATING-BEAM FATIGUE TESTS OF UNNOTCHED X76S-T ALLOY SPECIMENS.

Completely Reversed Stress Cycle

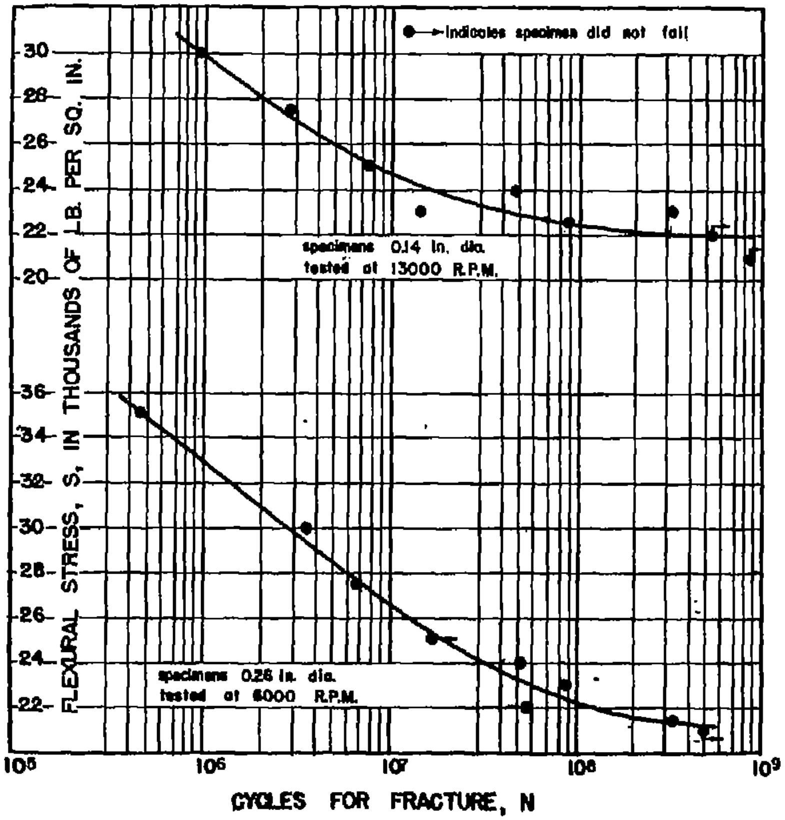


FIG. 15.- ROTATING-BEAM FATIGUE TESTS OF NOTCHED X76S-T ALLOY SPECIMENS.

COMPLETELY REVERSED STRESS CYCLE

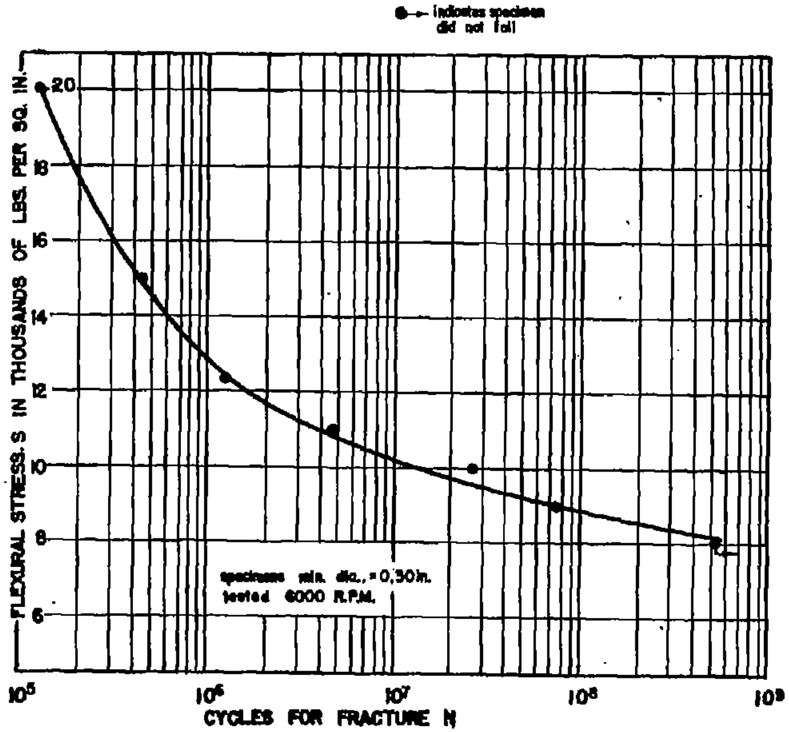
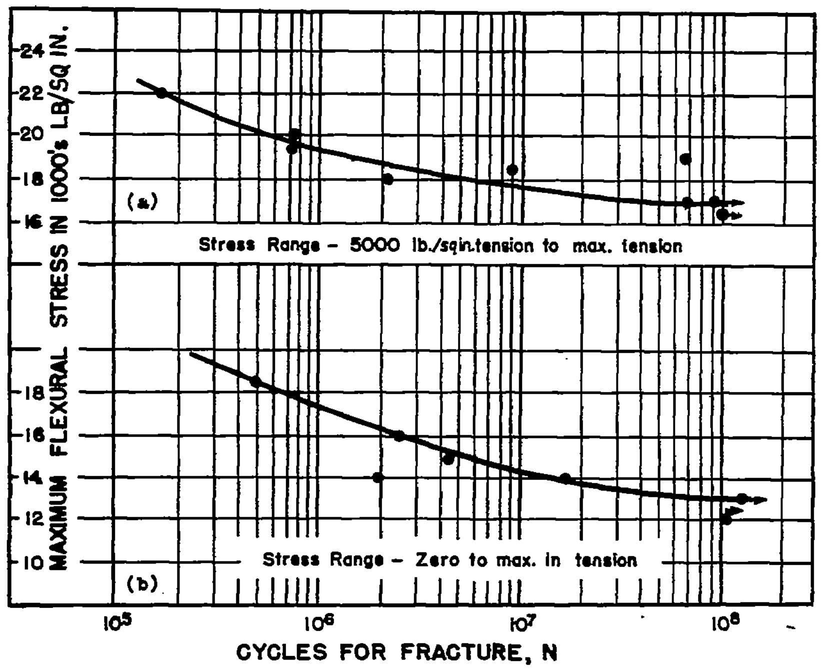


FIG. 16.- VIBRATORY BENDING FATIGUE TESTS OF NOTCHED SPECIMENS.

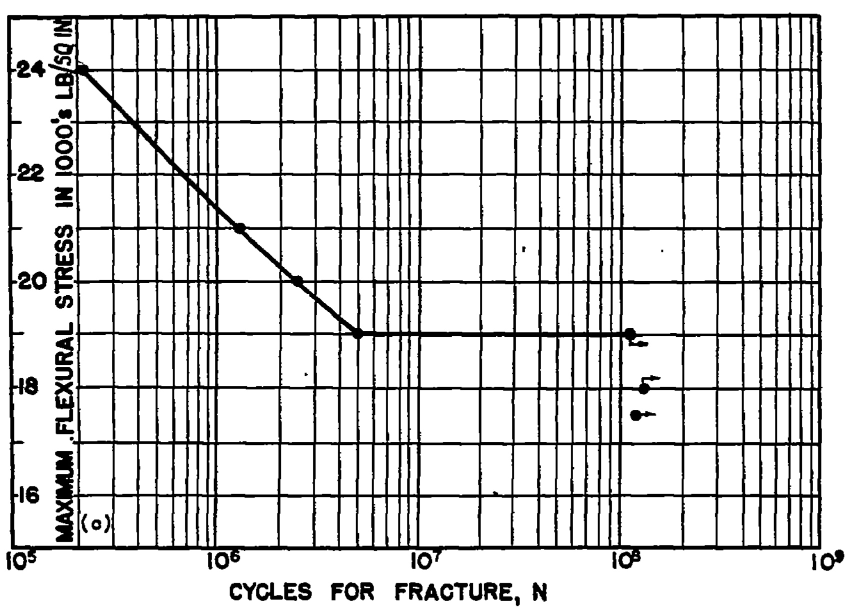
Specimens of Type Shown in Fig. 4(c)



Stress range-10,000 lb/sq in. tension to max. tension

specimen of type shown in fig. 4(c)

●→ indicates specimen did not fail



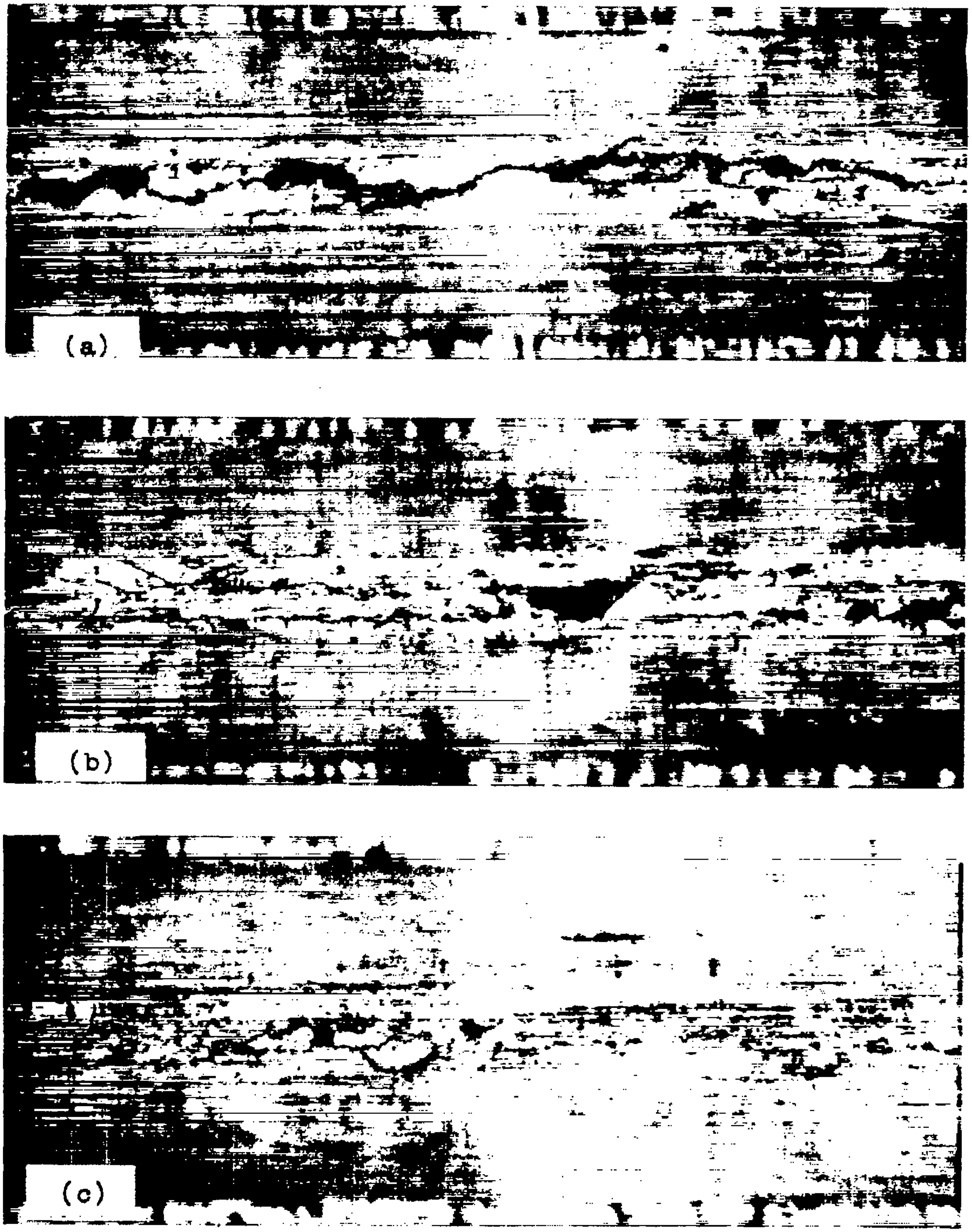


Figure 17a to c.- Cracks formed at root of notch in specimens tested in compressive stress cycles.
(Mag. 40X).

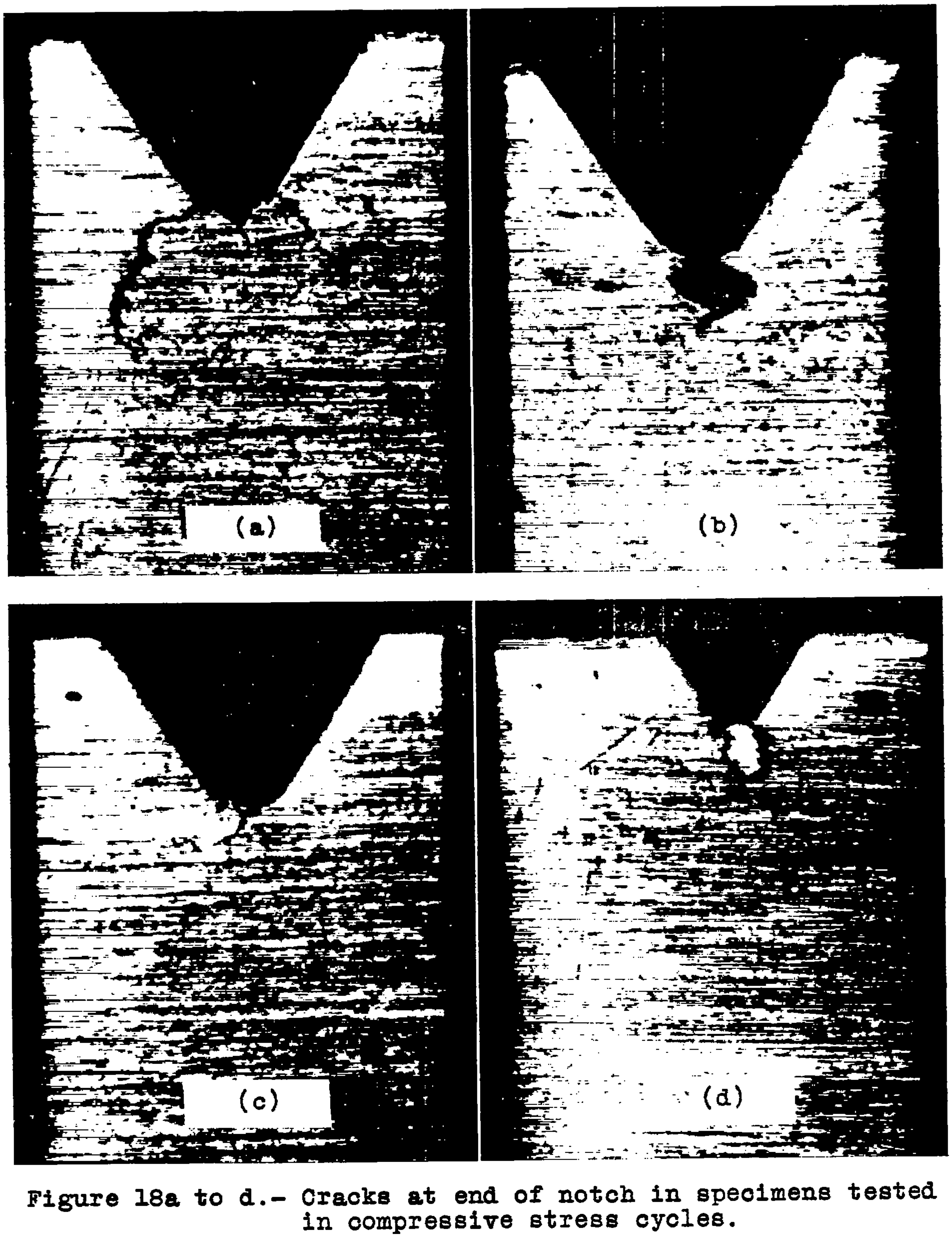


Figure 18a to d.- Cracks at end of notch in specimens tested in compressive stress cycles.

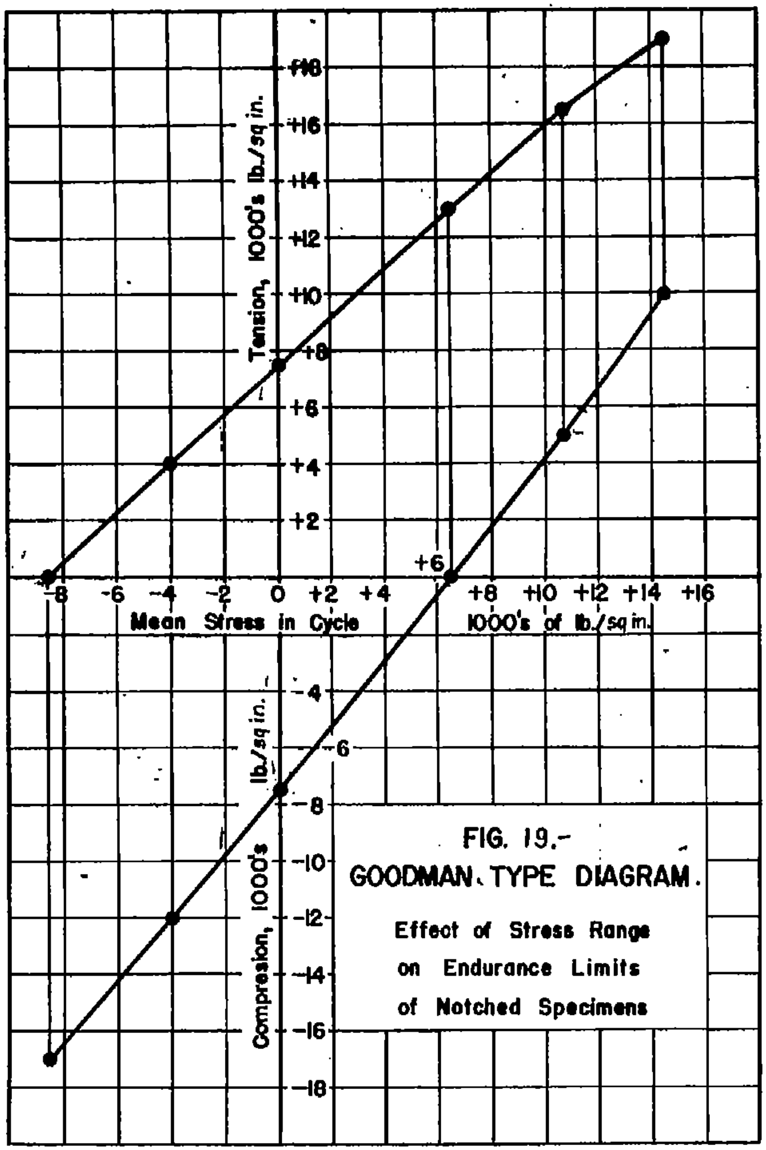


FIG. 19.-
GOODMAN TYPE DIAGRAM.
Effect of Stress Range on Endurance Limits of Notched Specimens

FIG. 20.- EFFECT OF MEAN STRESS ON ALTERNATING STRESS RANGE.